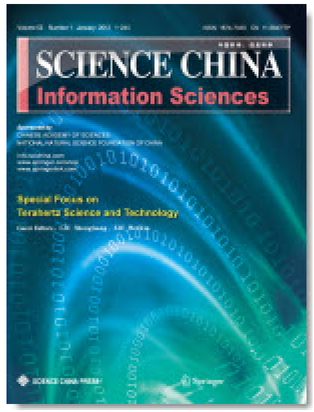

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• **LETTER** •

A multi-mode multi-skill project scheduling reformulation for reconnaissance mission planning

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Dear editor,

Planning multi-agents scheduling to conduct reconnaissance missions is the core of reconnaissance decision support system. A reconnaissance mission comprises several tasks and a network representing precedence relationships between them, where each task represents an area in which the agents perform information gathering. A precedence relationship imposes a restriction that one task can only start to be processed only if all its predecessor tasks have been completed. Reconnaissance mission planning aims to specify start time of each task and assign agents to it. There are many similarities between the project scheduling problem and reconnaissance mission planning. Both comprise several tasks (activities) with precedence relationships and aim to minimize the corresponding makespan. Multiple types of agent "skills" required to perform reconnaissance tasks, reconnaissance "agents," and characteristics of a reconnaissance task with multiple possible processing times correspond to the terms "multi-skill," "resource," and "multi-mode," respectively, defined in the project scheduling problem. Therefore, we model the reconnaissance mission planning problem as an extension of the multi-mode multi-skill project scheduling problem. The exact and meta-heuristic algorithms can not meet the computational time requirement of a reconnaissance mission (less than 1 s for 80 tasks), thus, only heuristic algorithms are suitable. There are only three studies discussing heuristic algorithms for solving the multi-mode multi-skill project scheduling problem [1–3], but all of them assume that mode information (task processing time when resource allocation is made) is known in advance, and transfer time between tasks is ignored, which is not representative of real reconnaissance missions. In this research, we propose a novel heuristic algorithm which is specially designed for reconnaissance mission planning.

Problem formulation. Following the model presented in [4] for the multi-skill project scheduling problem, the formulation of the reconnaissance mission planning problem can be obtained by adding Eq.(1) to calculate the mode information and Eq.(2) to consider the transfer time between tasks:

$$p_j = \max_{l \in L}\{\Gamma_j + \frac{A_j^l}{\sum\limits_{k \in R}\sum\limits_{t \in T} u_{kl} \times x_{jklt}}\},\ j \in V, \quad (1)$$

$$\sum_{t=ES_j}^{LS_j} ts_{jt} - \sum_{t=ES_i}^{LS_i} (t+p_i)s_{it} \geqslant \Delta_{ij} z_{ijk},\ i,j \in V, k \in R. \quad (2)$$

where p_j denotes the processing time of task j, t time step, V, K, L, T set of tasks, agents, skills and time steps, respectively, ES_j, LS_j earliest and latest start time of task j, Δ_{ij} transfer time between task i and j, u_{kl} value of skill l mastered by agent k, and Γ_j setup time for task j, respectively. s_{jt} equals 1 if task j starts at time t, and 0 otherwise. x_{jklt} equals 1 if resource k starts to work on task j with skill l at time t, and 0 otherwise. z_{ijk} equals 1 if resource k is transferred from i to j, and 0 otherwise. Equation (2) includes a nonlinear part, $p_i s_{it}$, and it is proposed to linearize the model.

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Proposition 1. By adding a new decision variable $w_{it} = p_i s_{it}$, $i \in V$, $t \in T$, the nonlinear component $p_i s_{it}$ can be converted to a linear convex expression by replacing it with w_{it} and its constraints: (1) $w_{it} \leqslant p_i^{max} \cdot s_{it}$; (2) $w_{it} \leqslant p_i^{min} s_{it} + p_i + p_i^{min}$; (3) $w_{it} \geqslant p_i^{min} \cdot s_{it}$; (4) $w_{it} \geqslant p_i^{max} \cdot s_{it} + p_i - p_i^{max}$. ($p_i^{max}$ and p_i^{min} are the upper and lower bound of p_i, respectively)

The proof of the proposition is presented in Appendix C.

Proposed algorithm. The proposed algorithm adopts a parallel schedule scheme, which is executed until there are unscheduled tasks, firstly by solving the Minimum Resource Feasible Match (MRFM) problem to find the optimal match between the available tasks and agents, which can ensure that the minimum skill requirement of each task is satisfied. If a redundant agent exists, then Additional Resource Allocation (ARA) is conducted to further reduce the processing time of the tasks. The MRFM is defined as follows:

$$\min \sum_{j\in W_t}\sum_{k\in Z_{W t}}\sum_{l\in L} m_{jkl} \tag{3}$$

$$\text{s.t.} \quad \sum_{j\in W_t}\sum_{l\in L} m_{jkl} \leqslant 1, \qquad k \in Z_{Wt}, \tag{4}$$

$$\sum_{k\in Z_{W_t}} m_{jkl}\cdot u_{kl} \geqslant SR_l^{min}(j), \qquad j\in W_t, l\in L, \tag{5}$$

$$m_{jkl}\in\{0,1\}, \qquad j\in W_t, k\in Z_{W_t}, l\in L. \tag{6}$$

where W_t, Z_{Wt} denotes the available tasks and agents at time t, $SR_l^{min}(j)$ minimum requirement of skill l of task j, and m_{jkl} decision variable to determine whether agent k is assigned to task j to perform skill l, respectively. The MRFM is solved by using the Gurobi optimizer. By solving the MRFM, the reconnaissance mission planning is decomposed into a number of small subproblems; thus, the utilization efficiency of agents is greatly improved.

A task rule and an agent rule are designed and used in the ARA. The task rule is defined as follows: (1) Calculate the priority value of task j as $SK_j - (p_j^{max} - p_j)$ and (2) Assign the highest priority value to the task that is in the critical path. We prioritize agents assignment to the task with the higher priority value. Two indicators are proposed for the agent rule of the ARA:

$$\Delta_j^{max} = s_j^* + p_j - \left(t + p_j^{min}\right) \tag{7}$$

$$\varepsilon_l = \frac{\sum_{k\in Z_{Wt}} u_{kl}}{(p_j^{max} - p_j)\sum_{l'\in L}\sum_{k\in Z_{W_t}} u_{kl'}} \tag{8}$$

where s_t^* denotes the expected start time of task j. The agent rule is defined as follows: (1) Agents with a transfer time larger than Δ_j^{max} can not be assigned to task j and (2) Agent performs the skill with the highest ε_l to the corresponding task. Using the proposed task and agent rules, the ARA runs until there is no feasible task or agent.

Experiment. A numerical experiment was conducted on three different sets of instances (Set 1, Set 2, and Set 3). Each set corresponded to 320 instances (total of 960 instances). The experiment uses ME, LFT, LPT, LST, SPT, MIS, MTS, GRPW, and GRPW* as comparison algorithms; the details of them are presented in [5]. Two boundary modes were considered for algorithm comparison: (1) Minimum requirement mode (Min) for a specific task-this mode requires the least resources, but has the longest processing time; (2) Maximum requirement mode (Max), which requires the most resources, but has the shortest processing time. The results show that the proposed method can meet the computation time requirement of reconnaissance mission planning and considerably outperforms the comparison algorithms with respect to the makespan of reconnaissance mission. The details of the experiment are presented in Appendix D.

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Supporting information Appendix A-E. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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